

A New Methodology for Velocity Estimation in Sheet and Rilled Overland Flow Using modified Manning's Roughness Coefficient

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1. Abstract

Manning's roughness coefficient for flow over bare soil is needed in order to determine other hydraulic parameters such as flow depth and velocity in overland flow, parameters needed to calculate streampower and shear stress in erosion process studies. A modified equation of Manning's n was developed to estimate flow velocity in shallow overland flow in experiments undertaken in a 5.8 by 1 m flume of the Griffith University Tilting flume Simulated Rainfall facility and adopted data from the literature. Even with the flow of water over a soil surface in which roughness elements are well inundated, and in less erosive situations where erosional bed forms are not pronounced, the magnitude of resistance coefficients in equations such as those of Manning, Darcy-Weisbach or Chezy vary with flow velocity (at least). Using both original laboratory and field data, and data from the literature, the paper examines this question of the apparent variation of resistance coefficients in relation to flow velocity, even in the absence of interaction between hydraulics and resulting erosional bed forms. Resistance equations are first assessed as to their ability to describe overland flow velocity when tested against these data sources. The result is that Manning's equation received stronger support than the Darcy-Weisbach or Chezy equations, though all equations were useful. The second question addressed is how best to estimate velocity of overland flow from measurements of slope and unit discharge, recognizing that the apparent flow velocity variation in resistance coefficients is probably a result of shortcomings in all of the listed resistance equations. A new methodology is illustrated which gives good agreement between estimated and measured flow velocity for both well-inundated sheet and rill flow. Comments are given on the predictive use of this methodology.

Key words: Flow velocity; Manning's equation; Darcy-Weisbach; sheet flow; rill flow

2. Introduction

When overland flow of water occurs in actively eroding rills, Govers (1992) and Nearing et al. (1997) have shown that the resistance offered to such flows is dominated by the bed forms generated by the erosion processes. In such actively eroding rills, these authors have shown that the classical form of decrease in the Darcy-Weisbach friction factor, f , with flow Reynolds number (Re) (Yoon and Wenzel, 1971) does not apply, and there would be similar limitations with alternative measures of hydraulic resistance.

In natural environments, overland flow can be sufficiently shallow that it flows around roughness elements which are not completely inundated by the flow. In such circumstances, Lawrence (1997) has shown that the degree to which the roughness elements are inundated plays a dominant role in determining the resistance offered to the flow by the surface. Using a wide range of data sources, Lawrence (1997) found that the frictional resistance could be approximately related to an "inundation ratio" defined as the ratio of flow depth to a scale of the surface roughness features.

Shallow flow over a stone-covered desert surface provides a particular example of flow that may not completely inundate all roughness elements. In this context, Abrahams and Parsons (1994) conceptually partitioned the resistance to overland flow into the following forms: grain resistance of the surface between the stones, form resistance (exerted by stones), wave resistance generated by disturbance of the free water surface due to flow over and around stones, and, finally, rain resistance due to impact of rainfall.

This paper gives particular attention to the velocity of overland flow. This is because this flow velocity is involved in the theory of a number of new-generation, physically based soil erosion models such as WEPP (Lafren et al., 1991), EUROSEM (Morgan et al., 1992), and GUEST (Rose, 1993; Misra and Rose, 1996).

The two questions considered in this paper are:

- 1) What ranking does experimental data give to the resistance equations associated with the names of Manning, Darcy-Weisbach and Chezy?
- 2) The second question considered is: how can flow velocity best be estimated?

3. Methods

Three types of experiments with runoff alone, rainfall alone, and rainfall plus runoff were undertaken in the 5.8 m by 1.0 m flume of the Griffith University Tilting-Flume Simulated Rainfall facility (or GUTSR)

described by Misra and Rose (1995). A rainfall rate of approximately 100 mm/h was used in these experiments. The soil used in the laboratory study was a Goomboorian loamy sand, an Albic Arenosol (FAO. Unesco, 1990) from the site of the field experiment. A series of volumetric fluxes ranging from 0.162 to 0.670 litres/s were used as runoff. The slope of the one-meter-wide flume was adjusted, ranging from 0.1 to 3.5% for sheet flow, and 0.5 to 10.5% for experiments with a single rectangular rill. Details of various combinations of fluxes and slopes are given in Table 1.

Table 1 Range of slope and unit discharge investigated in the laboratory and field experiments

Data source	Sheet/rill flow	Number of experiments	Slope range (%)	Unit discharge range ($\text{m}^2.\text{s}^{-1}$)
Laboratory experiments	Sheet	51	0.05-3.50	$0.16 \times 10^{-3} - 0.67 \times 10^{-3}$
	Rill*	23	0.5-10.50	$1.03 \times 10^{-3} - 2.39 \times 10^{-3}$
Field experiments	Furrow	19	3.2-5	$0.36 \times 10^{-3} - 8.21 \times 10^{-3}$
Guy et al. (1990)	Sheet	20	2 – 20	$0.01 \times 10^{-3} - 0.24 \times 10^{-3}$
Li and Abrahams (1997)	Sheet	105	2 – 9.5	$0.17 \times 10^{-3} - 3.67 \times 10^{-3}$

*A single rill was pre-formed in the flume's soil bed

The velocity of steady overland flow was determined using the salt tracing technique (Luk and Merz, 1992). Because the sandy loam had little structure, sodium chloride could be used as the conductivity trace, the output of an electrical conductivity meter placed at exit from the flume being electronically recorded. As shown in Figure 1, a pulse of salt solution was introduced at distance $X_0 = 1.8$ m from the top of the flume of length $L (= 5.8$ m), so that $(L - X_0) = 4$ m. The mean flow velocity was calculated from the mean time arrival in peak conductivity, which was well defined. The plot of conductivity versus time was close to symmetrical in most experiments, which were replicated three times. The maximum difference in arrival time between the peak and centroid of electrical conductivity was 13%, but was mostly much smaller.

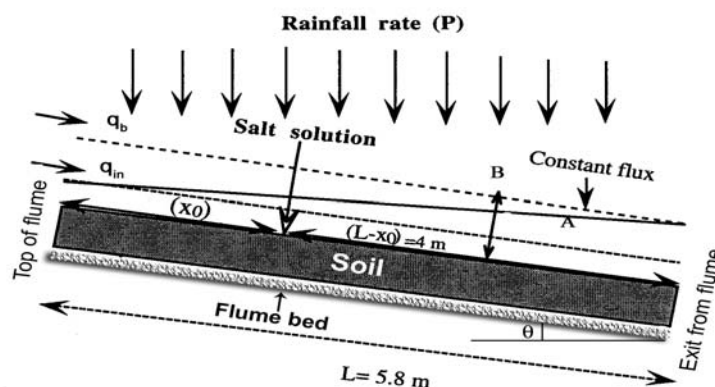


Figure 1 Schematic essentials of the laboratory equipments of Rouhipour (1997). Flow alone over the saturated soil bed, in which inflow and outflow are equal, has a water surface represented by the dashed lines. When rainfall of constant rate is added, the solid line indicates the increase in flux down the flume. The location of salt injection for the salt- tracing measurement of flow velocity is also indicated

Field experiments were located on a pineapple farm at Goomboorian, south-east Queensland, Australia (26° 36'S, 153° 18'E). Flow resistance experiments were carried out in furrows of width from 0.13 to 0.33 m formed between the raised planting beds. Water was introduced to the top end of 7 to 8m-long furrows for a sufficient time until steady flow conditions were achieved. Flow rate was measured by calibrated flow meters. Velocity of flow was assessed using an introduced dye. The velocity of the leading edge of the dye was multiplied by a reduction factor to give an approximate estimate of mean velocity. The value of 2/3 was chosen for this reduction factor (Li and Abrahams, 1997).

In addition to the author's experiments listed in Table 1, two sets of data from the literature were also used to test the relative applicability of alternative resistance equations in the absence of strongly eroding bed forms. Details of the literature data sets employed are given in Table 1.

3.1.Determination of resistance coefficients

The following expressions of Manning's n for sheet and rill flow were developed using classical Manning equation (Rouhipour et. al, 1999):

For sheet flow

$$n = (3/5)^{5/3} S^{1/2} (P/\bar{V})^{5/3} \frac{(L - x_0)^{5/3}}{\left[(q_{in} + PL)^{3/5} - (q_{in} + Px_0) \right]^{5/3}} \quad (1)$$

For rill flow

$$\bar{V} = \frac{\int_{x_0}^L V dx}{L - x_0} = \frac{S^{1/2}}{n(L - x_0)} \int_{x_0}^L R(x)^{2/3} dx \quad (2)$$

Where, in equation (1) \bar{V} is the mean flow velocity and x_0 is defined in Fig. 1 as the downslope distance at which the salt injection was applied. L is the length of flume, P is the rate of rainfall, S is the slope ($\sin \theta$, Figure 1) and q_{in} is the value of q at entry to the flume. In equation (2) $R(x)$, the hydraulic radius, $V(x)$ the velocity of flow are spatially variable down the flume (dx) in rilled flow experiments.

For rill flow, Manning's n was calculated from (2), with the integral being evaluated numerically. A similar procedure was followed for the other resistance equations.

4. Results

This subsection develops and illustrates a methodology for estimating velocity of overland flow of water from measurements of slope (S, the sine of the slope angle) and discharge per unit width of water (unit discharge, q). The data sources used in table 1. of the paper, in which flow velocity was also measured, were used to develop the methodology for estimating flow velocity both for rill and sheet flow based on modified Manning equation. Firstly, a general equation was developed for the velocity of flow, V (m/s) in both sheet flow and flow in a rectangular rill of width W, then basic equation was modified to the following form.

$$V = \frac{\left[1 - \exp(-Re/Re_0) \right] \left(\frac{q}{1 + \eta} \right)^{0.4}}{n_0^{0.6}} S^{0.3} \quad (3)$$

Where n_0 may be called a baseline value of Manning's n which is asymptotically approached at large Reynolds numbers, and Re_0 is a characteristic Reynolds number, which it can be broadly related to the transition from laminar to turbulent flow. Parameter η is related to the width-to-depth ratio: $\eta = 2D/W$.

Using the modified model in Equation (3) and the simplex downhill method for optimizing parameters n_0 and Re_0 , Table 2 summarizes results obtained for all the four sources of data described earlier in table 1.

Table 2 Summary model results for five sources of data described in the text

Data sources		Guy et al. (1990)	Li and Abrahams (1997)	Rouhipour (1997) Sheet	Rouhipour (1997) Rill	Rouhipour (1997) (Field)
Variable						
Model	No. of data points	20	105	51	23	19
	Re- range	11-239	583-13000	648-2680	3789-9541	367-6975
	Average V (m/s)	0.138	0.340	0.094	0.193	0.288
Equation (3)	n ₀	0.0095	0.0130	0.0140	0.0225	0.0257
	Re ₀	141	1851	794	2857	1360
	E	0.97	0.99	0.92	0.83	0.92
	RMSE in m/s (% of the mean)	0.021 (14.9%)	0.015 (4.4%)	0.016 (16.5%)	0.037 (18.9%)	0.037 (12.8%)
Straight line through origion	n	0.0110	0.0152	0.0189	0.0282	0.0263
	RMSE in m/s (% of the mean)	0.035 (25.3%)	0.061 (16.9%)	0.024 (26.5%)	0.040 (21.0%)	0.038 (13.3%)

RMSE: Root mean squared errors

From the estimated values of Re_0 shown in Table 2, it can be seen that Re_0 appears to be constrained by the Reynolds number range covered in the experiment. However, the maximum value of Re_0 is less than 3000, even in the rilled data of Rouhipour (1997), where Re was up to 9541. At the higher Reynolds number

characteristic of the rilled experiments of Rouhipour (1997), flow is likely to be fully turbulent; and, as shown in Table 2, introduction of the modification involving the exponential term in Re was least effective in reducing the RMSE compared to the basic straight line through the origin model.

For sheet flow, the value of n_0 obtained from the three sources of data shown in Table 2 is reasonably consistent, the value of n_0 with a rectangular rill being between two and three times higher.

The parameters in Table 2, estimated by fitting the modified model of Equation (3) to the five data sets were then used to estimate velocity of flow. Figure 2 compares these estimated with measured velocities, indicating the adequacy of Equation (3) as a model, provided parameters n_0 and Re_0 are determined.

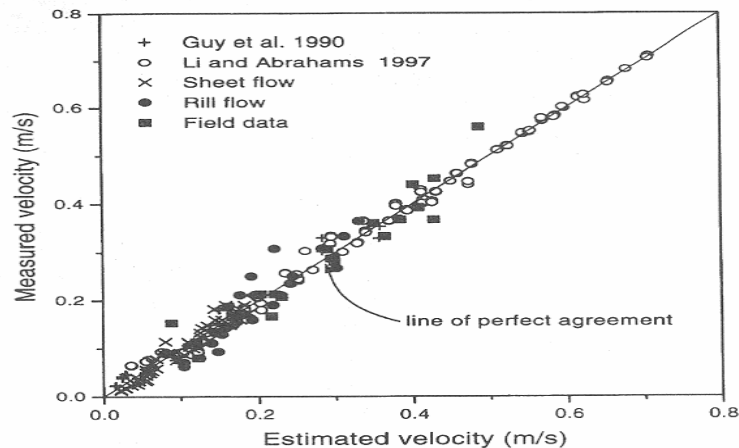


Figure 2 Measured flow velocity versus velocity estimated using the modified flow-velocity model given in equation 3. The data presented are those of sheet and rill data of authors's experiments together with data from literature listed in table 2.

5. References

- Abrahams, A. D. and Parsons, A. J. 1994. 'Hydraulics of interrill overland flow on stone-covered desert surfaces', *Catena*, 23, 111-140.
- Emmett, W. W. 1970. *The hydraulics of overlandflow on hillslopes*, US Geological Survey Professional Paper 662-A, 68 pp.
- FAO-Unesco. 1990. *Soil Map of the World: Revised Legend*, World Soil Resources Report 60, FAO, Rome.
- Govers, G. 1992. 'Relationships between discharge, velocity and flow area for rills eroding loose, non-layered materials', *Earth Surface Processes and Landforms*, 17, 515-528.
- Guy, B. T., Dickinson, W. T., Rudra, R. P. and Wall, G. 1990. 'Hydraulics of sediment-laden sheet flow and the influence of simulated rainfall', *Earth Surface Processes and Landforms*, 15, 101-118.
- Laflen, J. M., Lane, L. J. and Foster, G. R. 1991. 'WEPP: A new generation of erosion prediction technology', *Journal of Soil and Water Conservation*, 46, 34-38.
- Lawrence, D. S. L. 1997. 'Macroscale surface roughness and frictional resistance in overland flow', *Earth Surface Processes and Landforms*, 22, 365-382.
- Li, G. and Abrahams, A. D. 1997. 'Effect of saltating sediment load on the determination of the mean velocity of overland flow', *Water Resources Research*, 33, 341-347.
- Luk, S. H. and Merz, W. 1992. 'Use of the salt tracing technique to determine the velocity of overland flow', *Soil Technology*, 5, 289-301.
- Morgan, R. P. C., Quenton, J. N. and Rickson, R. J. 1992. *EUROSEM: Documentation Manual*, Silsoe College, Silsoe, UK.
- Nearing, M. A., Norton, L. D., Bulgakov, D. A., Larionov, G. A., West, L. T. and Dontsova, K. M. 1997. 'Hydraulics and erosion in eroding rills', *Water Resources Research*, 33, 865-876.
- Rose, C. W. 1993. 'Erosion and sedimentation', in Bonnell, M., Hufschmidt, M. M. and Gladwell, J. S. (Eds), *Hydrology and Water Management in the Humid Tropics*, Cambridge University Press, Cambridge, 301-343.
- Rouhipour, H. 1997. *Interaction between flow-driven and rainfall-driven soil erosion processes*, unpublished PhD thesis, Griffith University, Queensland, Australia.
- Yoon, Y. N. and Wenzel, H. G. 1971. 'Mechanics of sheet flow under simulated rainfall', *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, 97, HY9, 1367-1386.